

EXAMINATION METHOD AND APPARATUS

FIELD OF THE INVENTION

The invention relates to a method and an apparatus for detection of ionizing radiation.

5 BACKGROUND OF THE INVENTION AND RELATED ART

Radiographic imaging detectors comprising an array of small sensors to capture a radiation-generated image are well known in the art. A collimated radiation beam is intensity modulated as it passes through a radiation-absorbing subject and the
10 transmitted beam as detected thus represents an inverted image of the absorption by the subject, which in turn is related to the elemental composition, density, and thickness of the subject.

To improve contrast the broadband radiation from an X-ray tube
15 is heavily filtered before being used for radiographic purposes. It is well known that at X-ray photon energies typically used, the photoelectric absorption is decreased as a power law as the X-ray photon energy increases, while unwanted scattering is increased.

20 For soft tissue the photoelectric absorption is decreasing rapidly at energies above about 20 keV and this higher energy X-ray radiation does not contribute to the image recorded, but reduces the contrast in the image. Thus, higher energies are filtered out from the radiation.

25 SUMMARY OF THE INVENTION

A problem with the known kind of approach is that most X-ray tubes have low efficiency at such low photon energy as 20 keV,

i.e. the number of X-rays per unit power supplied to the tube is low.

Further, all X-ray tubes emit radiation within a wide energy spectrum. Typically, metallic foils filter the radiation from the X-ray tube, but simultaneously the flux of X-rays is reduced. Thus, large load has to be put on the X-ray tube to obtain a reasonable radiation flux downstream the metallic foils. Also, the relatively low flux affects the exposure time in an adverse manner, i.e. makes it long, which obviously limits the applicability of the technique.

Another issue of high importance is the radiation dose to the subject in case it is a living organism or part thereof. While the development of efficient collimators, appropriate filters, and sensitive detector arrays during the last decades have effectively reduced the radiation dose; still there is much to do. Further reduction of the radiation dose is a driving mechanism in detector design of today.

A main object of the invention is therefore to provide a method and an apparatus for examination of a subject, which overcome the above-identified problems as being related with the prior art.

In this respect there is a particular object to provide such a method and such an apparatus, which provide for the deposition of only small amounts of energy in a subject to be examined.

A further object of the invention is to provide such a method and such an apparatus, which provide for the possibility of using broadband radiation for the measurement.

A still further object of the invention is to provide such a method and such an apparatus, wherein radiation in a spectral

range is used, in which the risk of under- or over exposing some areas of the image is reduced.

Yet a further object of the invention is to provide such a method and such an apparatus, wherein radiation over a wide energy range, and especially at high photon energies, can be detected with high efficiency.

These objects, among others, are attained by methods and apparatuses as claimed in the appended claims.

The inventors have found that by *preventing* Compton scattered radiation from being detected, and by providing ionizing radiation within a *spectral range* such that more, preferably much more photons, of the ionizing radiation are Compton scattered than absorbed through the photoelectric effect in the subject to be examined, an entirely new field of radiology opens up. Since the probability of scattering is essentially the same for a broad spectrum of photon energies, broadband radiation including higher energies can be used for the detection.

Variations in an image, captured at photon energies high enough to mainly obtain Compton scattering in the subject, are substantially due to the *density* only of the examined subject, provided that its thickness is constant, or known and corrected for. This is true since the attenuation coefficient for Compton scattering at photon energies of 10-300 keV is only weakly dependent on atomic number and photon energy. This is in sharp contrast to photoelectric absorption, which is heavily dependent on energy, and even more dependent on atomic number. Thus, the radiation image obtained is essentially a shadow image of the density variations in the subject to be examined.

In some radiographic applications, however, such as soft tissue applications including e.g. mammography, the density variations may be very small, and therefore the contrast in the recorded images is very low. According to the present invention, a suitable *contrast-enhancing agent* is therefore introduced into the subject to be examined. The suitable should modify the *density* of the subject to be examined and introduce density gradients into there. The density of the contrast-enhancing agent may be higher or lower than the density of the subject, but is preferably lower than the density of the subject. For instance, an ultrasound contrast agent may be employed. Contrast agents comprising or capable of generating dispersions of gas microbubbles are preferred, since such dispersions are particularly efficient due to the low density and ease of compressibility of the microbubbles. Thus, ordinary contrast enhancing agents for X-ray diagnostics, such as iodine, which introduce atomic number gradients into the subject rather than density gradients, are less suitable. Further, the ultrasound contrast agent administered to the subject should be sufficiently stable in vivo to be recirculated in the blood stream following administration, so that it may become equilibrated in the blood pool prior to imaging.

Preferably, Compton scattered radiation is prevented from being detected by means of a one-dimensional gas ionization detector including two electrodes, between which an ionizable gas is located, and a radiation entrance arranged such that said ionizing radiation enters said detector sideways between the electrodes, and electrons liberated by interaction between the ionizing radiation and the gas are accelerated in a direction essentially perpendicular thereto, wherein the distance between the electrodes is kept short to essentially only allow

radiation collimated in a plane between the electrodes to ionize the gas. Further, the detector preferably employs electron avalanche amplification; wherein only radiation collimated in a very thin plane closest to the cathode electrode will be amplified sufficiently to essentially contribute to the signal as detected.

An advantage of the present invention is that if broadband radiation is used for the detection, there is less need of thick filters, the efficiency of the radiation source is increased, the load on the radiation source can be lowered, and the exposure time can be reduced due to the higher photon flux.

Further, since a *scattered* photon deposits only a fraction of its energy in a subject, whereas a *photoelectrically absorbed* photon deposits all its energy, the dose to the subject is reduced.

In a particular preferred embodiment of the present invention the above-mentioned novel examination method based on scattering rather than absorption, is combined with an ultrasound examination method. Here, the contrast-enhancing agent can be administered to the subject, after which the above-mentioned novel examination method based on scattering and the ultrasound examination method are performed, preferably simultaneously, using the same contrast-enhancing agent. This is particularly advantageous for mammography examinations, wherein the above-mentioned novel examination method based on scattering provides for the detection of a high-quality image of a breast to be examined causing an extremely low dose to the subject. For instance, the dose may be 20-100 times lower than in prior art X-ray mammography examinations. The ultrasound examination provides an

ultrasound image, which serves as a complement for diagnosis. Some tumors will be better visualized in the ultrasound image.

Further characteristics of the invention, and advantages thereof, will be evident from the detailed description of preferred embodiments of the present invention given hereinafter and the accompanying Figs. 1-4, which are given by way of illustration only, and thus are not limitative of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram illustrating photoelectric absorption, Compton scattering, pair production and total attenuation coefficients for human tissue as a function of X-ray photon energy, and a continuous X-ray spectrum of a typical X-ray source for use in the present invention.

Fig. 2 illustrates schematically an apparatus for radiography used in the present invention.

Fig. 3 is a flow diagram of a method according to a preferred embodiment of the present invention.

Fig. 4 illustrates schematically an apparatus for radiography according to another preferred embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

As can be seen in Fig. 1, which is a schematic diagram illustrating photoelectric absorption, Compton scattering, pair production and total attenuation coefficient μ_{PE} , μ_{CS} , μ_{PR} , μ_{TOT} for human soft tissue as a function of X-ray photon energy E , the photoelectric attenuation coefficient μ_{PE} decreases as a power law with photon energy, and at about 25 keV the Compton

scattering attenuation coefficient μ_{CS} is comparable with the photoelectric absorption attenuation coefficient μ_{PE} . Between about 30 and several hundred keV the Compton scattering attenuation coefficient μ_{CS} is completely dominating, whereas at higher photon energies (in the order of 1 MeV) the probability for pair production is increasing rapidly, and becomes the dominating interaction process. While Fig. 1 is illustrating an example only for human soft tissue, the relative overall structure of the diagram holds for a large variety of matter.

The Compton scattering attenuation coefficient μ_{CS} is fairly constant over a large range of photon energies. It can be seen in Fig. 1 the Compton scattering attenuation coefficient μ_{CS} for soft tissue is fairly constant between photon energies of about 30 and several hundred keV.

Further, the photoelectric absorption attenuation coefficient μ_{PE} is heavily dependent on the atomic number of the elements, of which the matter is comprised, whereas the Compton scattering attenuation coefficient μ_{CS} is only very weakly dependent on the atomic number.

Still further, the transmission through matter is dependent exponentially on the total attenuation coefficient μ_{TOT} , on the density ρ of the matter, and on the thickness t of the matter according to:

$$\text{Transmission} \sim \exp[-(\mu_{TOT} * \rho * t)]$$

Thus, provided that ionizing radiation with photon energies high enough so that Compton scattering dominates over photoelectric absorption is passed through matter, the transmission through there is only very weakly dependent on atomic number of the

matter, and the actual photon energy, but strongly dependent on the density of the matter. This is in sharp contrast to the case where photoelectric absorption is the dominating interaction mechanism. Here, the transmission through the matter is not only
5 strongly dependent on the density of the matter, but also on the atomic number of the matter as well as on the actual photon energy employed. Thus, if ionizing radiation with photon energies high enough so that Compton scattering dominates over photoelectric absorption was used, it can be broadband radiation
10 without having to perform complex calculations to compensate for any strong photon energy dependence.

A typical continuous X-ray spectrum from an 30 kV wolfram-based X-ray tube as filtered by a rhodium filter for use in e.g. mammography examinations according to prior art is schematically
15 indicated in Fig. 1 by a dash-dotted line. Here, photoelectric absorption dominates over Compton scattering. A broadband X-ray spectrum from an 80 kV tungsten-based X-ray tube as filtered with a copper filter is indicated by a dashed line. The broadband radiation spectrum is displaced towards higher photon
20 energies, at which Compton scattering dominates over photoelectric absorption.

Fig. 2 illustrates schematically, in a side elevation view, an apparatus for radiography for use in the present invention. The apparatus comprises, as seen from left to right, an X-ray source
25 1, a filter arrangement 4, an optional source aperture 5 and a detector device 11.

The X-ray source may be a tungsten-based X-ray tube emitting an X-ray radiation beam within a wide energy spectrum. The beam is filtered by means of the filter arrangement 4 at the output of
30 the X-ray source 1. The filter arrangement 4 differs from a conventional filter in the sense that it transmits higher

energies, and preferably a much wider spectrum, such as e.g. the broadband X-ray spectrum illustrated in Fig. 1. The radiation beam as filtered is subsequently passed through the optional source aperture 5 to collimate the beam. Preferably, the shape and size of the source aperture 5 is adapted to the particular size and kind of detector device 11. Thus, given a one-dimensional detector device, the aperture 5 is designed with a slit-shaped radiation transparent window, and given a rectangular two-dimensional detector device, the aperture 5 is preferably designed with a rectangular radiation transparent window.

The source collimator is optional and is used to reduce the dose to the subject to be examined in case the subject is a living organism or part thereof, by producing a beam of X-rays, which only illuminates the sensitive areas of the detector device 11.

The radiation beam 3 as filtered and optionally collimated enters a region, where a subject, subject-matter, matter, object or patient 7 to be imaged is located. In the subject 7 some photons may be photoelectrically absorbed, some may be Raleigh and Compton scattered (indicated by rays 3a in Fig. 1), and some photons may be converted into electrons and positrons in a pair production process, where these electrons and positrons may give rise to emission of X-ray photons (indicated by rays 3b in Fig. 1). The various processes depend on elemental composition of the subject 7 and on the photon energies of the incident radiation beam 3.

The radiation beam transmitted through the subject 7 without being deflected is detected by the detector device 11, while the scattered radiation is prevented from being detected. Typically, however, small amounts scattered radiation might enter into the detector device 11 and blur the image recorded.

According to the present invention the filter arrangement 4 is adapted to the elemental composition of the subject 7 to be imaged in a manner such the radiation beam as filtered is within a spectral range so that more photons of the radiation beam as filtered are Compton scattered than absorbed through the photoelectric effect in the subject 7, i.e. so that Compton scattering dominates over photoelectric absorption.

In the case of human soft tissue, such as breast tissue, the filtered radiation may be broadband X-ray radiation between 10 and 300 keV (i.e. similar to the broadband radiation spectrum of Fig. 1), preferably between 20 and 100 keV, and more preferably above 30 keV. In other applications the filtered radiation may be radiation above 30 keV.

Alternatively, the filtered radiation is in a spectral range such that at least 2 times, more preferably at least 5 times, and most preferably at least 10 times more photons of the filtered radiation are Compton scattered than absorbed through the photoelectric effect in the subject 7. If possible the filtered radiation should be in a spectral range, at which photoelectric absorption does not essentially occur in the subject 7.

The detector 11 has preferably an elongated opening for entry of the ionizing radiation; and a row of individual detector elements arranged essentially parallel with the elongated opening; and is of the kind wherein charges or photons generated by interactions between the ionizing radiation and a detection medium within the detector and travelling in a direction essentially perpendicular to the ionizing radiation, are detected by the row of individual detector elements.

The detector is preferably a gaseous-based parallel plate detector operating in avalanche amplification mode, wherein the signals in the individual detector elements originate essentially only from ionization within a thin layer, which may be at least 2-5 times thinner than the inter-plate distance. This advantageous behavior is obtained as the amplification is exponential and electrons liberated closer to the individual detector elements will not be able to produce signals strong enough.

For further details regarding different kind of detectors for use in the present invention, reference is made to the following U.S. Patents by Tom Francke et al. and assigned to XCounter AB of Sweden, which patents are hereby incorporated by reference: Nos. 6,118,125; 6,373,065; 6,337,482; 6,385,282; 6,414,317; 6,476,397; 6,477,223; 6,518,578; 6,522,722; 6,546,070; 6,556,650; 6,600,804; and 6,627,897.

Alternatively, the detector device 11 may more generally be any one- or two-dimensional detector, which is capable of discriminating scattered photons to a large extent. The detector may preferably any of a TFT-based detector; a scintillator-based detector; a solid state detector such as a CMOS- CCD-, CdZn- or CdZnTe-based detector; a gaseous-based detector; or a combination thereof, and is advantageously provided with an anti-scatter device, particularly an array of radiation-transparent channels arranged in front of the detector.

In order for the invention to operate properly, the scattered radiation has to be discriminated from being detected to an especially large extent. Preferably at least 90%, more preferably at least 99%, and most preferably at least 99.9% of the Compton scattered radiation in the subject 7 is prevented

from being detected. The parallel plate detector described above has been shown to easily fulfill such a requirement.

By means of primarily using ionizing radiation at photon energies where Compton scattering dominates over photoelectric absorption, and by detecting the transmitted radiation separate from the radiation scattered in the subject, a number of advantages arise:

- Since the radiation is primarily scattered off the subject 7 and not absorbed in it, the radiation dose to the subject is reduced. At photon energies of 50 keV a Compton scattered photon deposits only about 10% of the energy compared to a photoelectrically absorbed photon.
- The filters may be made thinner since the radiation has not to be that heavily filtered (due to the Compton scattering attenuation coefficient compared to the photoelectric absorption attenuation coefficient). Less radiation is scattered in a thin filter than in a thick filter, which means that the scattered radiation from the filter arrangement 4 is reduced as compared with a conventional filter arrangement.
- The efficiency of the X-ray tube is increased since larger portions of the emitted spectrum are usable. This means also that the load on the X-ray tube can be lowered. The exposure time can also be reduced due to the higher X-ray photon flux obtainable.
- The attenuation coefficient for Compton scattering at photon energies of 10-300 keV is only weakly dependent on atomic number and photon energy, and thus variations in the image captured are essentially due to variations in

the density of the subject only, provided that the subject thickness is constant, or known and corrected for.

The last advantage can in some applications be a drawback. If the density variations are very small as they can be in some mammography examinations the contrast in the image may be too low.

However, a solution to this comprises, in accordance with the present invention, to use a contrast-enhancing agent, which is suitable for the above-described X-ray imaging technique. The suitable contrast-enhancing agent should modify the density of the subject to be examined and introduce density gradients into there. For instance, an ultrasound contrast agent may be employed. Contrast agents comprising or capable of generating dispersions of gas microbubbles are preferred, since such dispersions are particularly efficient due to the low density and ease of compressibility of the microbubbles. Thus, ordinary contrast enhancing agents for X-ray diagnostics, such as iodine, which introduce atomic number gradients into the subject rather than density gradients, are less suitable. Further, the contrast agent administered to the subject should be sufficiently stable in vivo to be recirculated in the blood stream following administration, so that it may become equilibrated in the blood pool prior to imaging. Suitable contrast agents, which have been described for ultrasound examinations, and which are suitable in the present invention are disclosed in the U.S. Patents Nos. 6,645,147; 6,595,925; 6,547,738; 6,409,671; 6,375,931; 5,772,984; 5,567,415; and 5,236,693, the contents of which being hereby incorporated by reference.

Thus, a method for examination of a subject according to a preferred embodiment of the invention, being illustrated in Fig. 3, comprises the following steps.

5 Ionizing radiation is provided, in a step 31, within a spectral range so that more photons of said ionizing radiation are Compton scattered than absorbed through the photoelectric effect in the subject to be examined. That is, the Compton scattering should be the dominating interaction mechanism of the interactions of the incident ionizing radiation with the
10 subject. Preferably, the energy of the radiation photons should be selected so as to minimize the amount of photoelectric absorption in the subject given all other constraints, such as e.g. characteristics of the radiation source used, available radiation filters, required radiation
15 flux, etc., as imposed by the particular application. Any of the radiation spectrum profiles disclosed in this description may be employed depending on the actual circumstances.

A suitable contrast-enhancing agent is, in a step 32, administered to the subject to be examined, where the
20 contrast-enhancing agent introduces density variations in said subject. The contrast-enhancing agent may be any of the contrast-enhancing agents indicated above.

The ionizing radiation is then, in a step 33, directed towards and passed through the subject. In the subject, various
25 interactions take place. However, the dominating interaction mechanism of the incident ionizing radiation with the subject is Compton scattering, which, as has been discussed above, is dependent on density, but fairly independent on atomic number and photon energy (within a given range).

The ionizing radiation as transmitted through said subject without being deflected is, in a step 34, detected spatially resolved, while the Compton scattered radiation in the subject is essentially prevented from being detected. For this purpose, any of the above-described scattering-rejection detecting apparatuses can be employed. If the photoelectric absorption can be neglected, the signals recorded can be arranged to form an image of the transmission, which would be a true inverted image, or shadow image, of the Compton scattering in the subject. Therefore, the image formed reveals spatially resolved density variations in the subject - density variations originally present in the subject as well as those introduced by the contrast-enhancing agent.

In a further preferred embodiment of the present invention, being illustrated in Fig. 4, the above-mentioned novel examination apparatus based on scattering rather than absorption, is combined with an ultrasound examination apparatus.

The X-ray detector device 11 and the X-ray source arrangement 41 including the X-ray source 1, the filter arrangement 4, and the optional source aperture 5 of Fig. 2, are arranged on opposite sides of a subject to be examined, such as a breast 42. An ultrasound examination apparatus 43 is arranged adjacent to the X-ray detector device 11. A device 44, such as a syringe, is provided for administering an ultrasound contrast-enhancing agent to the subject 42.

Prior to examination the ultrasound contrast-enhancing agent is administered to the subject 42, after which the breast is imaged, preferably simultaneously, by the X-ray detector device 11/ X-ray source arrangement 41 combination and the

ultrasound examination apparatus 43 using the very same contrast-enhancing agent administration.

This is particularly advantageous for mammography examinations, wherein the above-mentioned novel examination method based on scattering provides for the detection of a high-quality image of a breast of the subject to be examined, causing an extremely low dose to the subject. For instance, the dose may be 20-100 times lower than in prior art X-ray mammography examinations. The ultrasound examination provides an ultrasound image, which serves as a complement for diagnosis. Some tumors will be better visualized in the ultrasound image.